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RELATIONSHIPS BETWEEN SEA-LEVEL ISOBARS AND THE WIND SPEED AT 900 METRES

By C. J. BOYDEN

Introduction.—In forecasting the wind speed just above the earth's friction layer it is customary to apply the geostrophic relationship to the sea-level isobars and then make a rough adjustment for the cyclostrophic term if the flow has pronounced curvature; precise measurement is difficult because the cyclostrophic term involves the curvature of the trajectory, not of the isobars. Allowance can also be made for the lag of the wind behind the equilibrium speed during acceleration and deceleration. Deviations from balanced flow are usually accounted for in these ways when they are observed, but in forecasting a wind speed they are largely disregarded because the major problem, as well as the main source of error, is the forecasting of the pressure gradient. Nevertheless, it was thought to be of interest to make an assessment of the lag of the wind, both in magnitude and time, when the pressure gradient is changing. In the course of this work it was found that the gradient wind speed, based on isobaric curvature, was very different from the true wind, and empirical relationships were found which should be useful to the forecaster. All conclusions were based on wind speeds measured by the Crawley radar at a height of 900 m (a standard level in the reports) as compared with geostrophic and gradient winds measured over south-east England on hourly charts drawn in the Central Forecasting Office. Only the winter months October to March were studied.

The main causes of differences between reported 900 m wind speeds and gradient wind speeds are the following:

- (i) Both the wind and the isobaric pattern are subject to small-scale variations. The radar wind speed is a measurement over two or three minutes; this may not be representative of the speed over a longer period and may not therefore match the pressure pattern on the synoptic scale.
- (ii) The wind varies between 900 m and sea level. Since the average wind increase with height between 850 mb and 700 mb is about 2 kt/km, it seems reasonable to assume about 2 kt as the average geostrophic difference between 900 m and sea level.

- (iii) The geostrophic scale used was based on an air temperature of 10°C . This introduced an average error of about four per cent and this was regarded as cancelling (ii), above.
- (iv) Inaccuracies in the isobars are inevitable, partly through inaccurate drawing to the observations and partly because of pressure errors. These inaccuracies should be small over south-east England, since observations there are comparatively plentiful.
- (v) There may be radar wind errors, either random or systematic. Evidence is given for a systematic error.
- (vi) All gradient winds used in the comparisons were based on isobaric curvature, although some estimates are given of the mean errors involved.
- (vii) There is a lag in the adjustment of the wind to a changing pressure gradient. This adjustment may become necessary through a change of pressure gradient with time or because air moves through the pattern to a place where the gradient is stronger or weaker.

Ideally an investigation of this kind would be made following the movement of a parcel of air. This is impossible with a normal observational network unless assumptions are made about the ageostrophic flow which is the subject of the investigation. The local change of pressure gradient in the Crawley area over a 3-hour period was therefore taken as a measure of the change undergone by a parcel of moving air. Thus acceleration was defined by a local increase of pressure gradient (measurement being made along about 200 miles of isobar), and the acceleration of the moving air was regarded as equal to the local increase of geostrophic wind speed during the period. Over periods of three or even five hours the approximation was regarded as satisfactory on most occasions and for most purposes because of the small variations of pressure gradient and curvature usually found at any instant along such a short trajectory. Only when the isobars had pronounced curvature and were changing direction with time did it seem that this relationship required substantial modification. In order to verify this a check was made using the 73 occasions of tightening cyclonic isobars on which Table II was based. The pressure gradient was measured at Crawley and then on the chart of three hours before at a point 130 miles upwind from Crawley. This distance was the average 3-hour travel of the air, and the trajectory was taken along the isobars of the later of the two charts. On the majority of occasions there was an increase of geostrophic wind on the air as it moved to Crawley. The average increase was about a quarter of the initial speed, whereas the local increase of geostrophic wind at Crawley over the three hours was about a third. The difference is accounted for mainly by some bias in selection (see below) and to a small extent by the cross-isobar flow, whereby the air moved from a region of higher pressure and normally weaker gradient than was assumed. It therefore appeared that for most isobaric curvatures the local change over three hours adequately represented the change in speed of the moving air. This relationship doubtless depends on the fact that the air moves only slowly through medium-scale features of the pressure pattern, and it may not hold at high levels in the atmosphere.

Radar wind errors.—In order to assess the accuracy of radar wind speeds at 900 m a comparison was made with geostrophic wind speeds on occasions

when the isobars were straight and the wind was steady. The criterion for steadiness was that the geostrophic wind, measured to the nearest five knots, was within five knots of the geostrophic speed at the same place three hours earlier. The period October to March in each of the winters 1959-60, 1960-61 and 1961-62 yielded a total of 174 pairs of values. Figure 1 shows the relationship between the geostrophic wind speed and the average excess over the 900 m wind speed from Crawley. The scatter of the points is fairly large, partly because of the inevitable bias in measuring a wind to the nearest 5 knots.

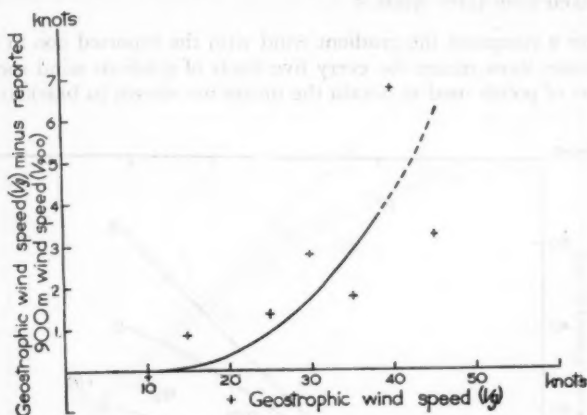


FIGURE 1—DIFFERENCE BETWEEN GEOSTROPHIC WIND SPEED AND REPORTED 900 M WIND WITH STRAIGHT STEADY ISOBARS

Nevertheless, there is undoubtedly a discrepancy between the two wind speeds which is small below 20 knots but increases rapidly with stronger winds. The cause appears to be that the 900 m speed is calculated from a horizontal displacement which takes place partly within the friction layer. The balloon rises at 350 m/min and the displacement is measured between the end of the first and third minutes, or sometimes between the first and fourth. The stronger the wind the greater will be the increase of speed with height and thus the greater will be the difference between the reported 900 m wind and the true speed. The magnitude of the discrepancies shown in Figure 1 is in quite good agreement with what is to be expected from the variations of speed with height found by pilot-balloon measurements.¹

This explanation requires that there should be a corresponding discrepancy in direction, the reported 900 m wind being slightly backed from the true direction. Since radar wind directions are reported only to the nearest 10° a detailed analysis was not possible. Nevertheless a limited comparison for steady geostrophic winds of 35-40 knots showed the reported wind to be backed from the isobar by about 4° on the average.

The cyclostrophic term in steady anticyclonic flow.—It is not uncommon to find that anticyclonic isobars give a gradient wind speed markedly higher than the observed 900 m wind speed. It is then usual to suppose that the

trajectory is straighter than the isobars because of the turning of the isobars as time goes on, as for example if there exists a small moving ridge. In order to ascertain whether a difference in speed could occur with little indication on the chart, a comparison was made on occasions of steady anticyclonic isobars. Steadiness was again defined by there being no change of geostrophic wind exceeding five knots in three hours in the vicinity of Crawley. Changes in curvature or direction in the three hours were ignored as these were usually small and were not thought to have any effect on mean values. Observations were taken from three winters.

Figure 2 compares the gradient wind with the reported 900 m wind speed. The crosses show means for every five knots of gradient wind speed, and the numbers of points used to obtain the means are shown in brackets. OA is the

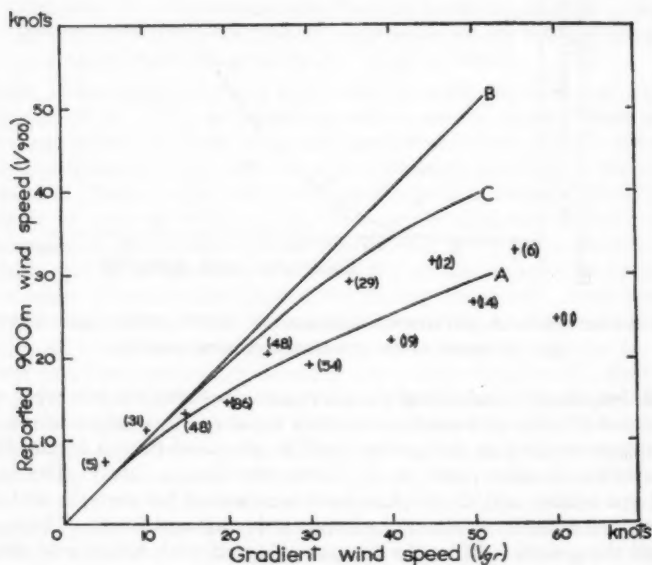


FIGURE 2—GRADIENT WIND SPEED COMPARED WITH 900 M WIND SPEED IN STEADY ANTICYCLONIC FLOW

line of best fit. (The alternation of the crosses about OA is due to the use of a limited number of radii of curvature, and through geostrophic winds being measured only to the nearest five knots.) The line OB would represent equality between the gradient wind and the reported 900 m wind speed, whereas OC, drawn from the data of Figure 1, represents the adjustment to OB for the systematic radar wind error.

Since OA is a substantial distance from OC, it is clear that the gradient wind speed, as determined from steady anticyclonic isobars, seriously overestimated the true wind.

Figure 3 is based on the same set of observations, but here the geostrophic wind has been plotted instead of the gradient wind. The lines OA, OB and OC have the same significance as in Figure 2. It will now be seen that the mean geostrophic wind speed was within one or two knots of the true 900 m wind at all speeds. In other words, it appears that steady anticyclonic flow can be treated as though no cyclostrophic term exists. Whether this is true for all isobaric curvatures has yet to be determined.

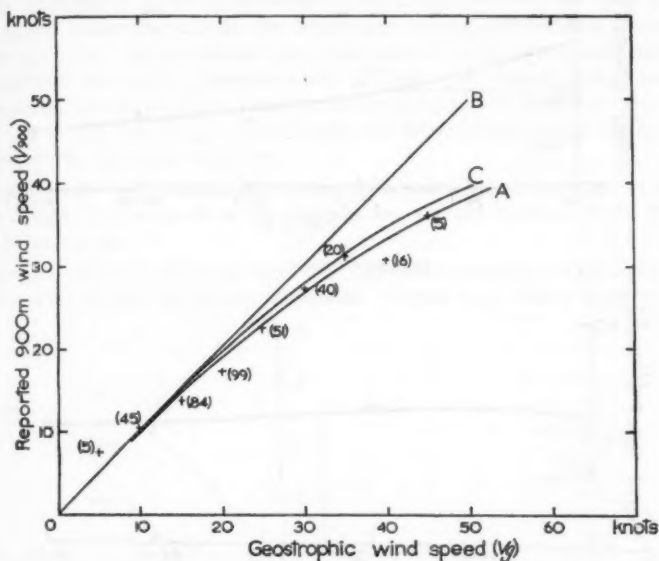
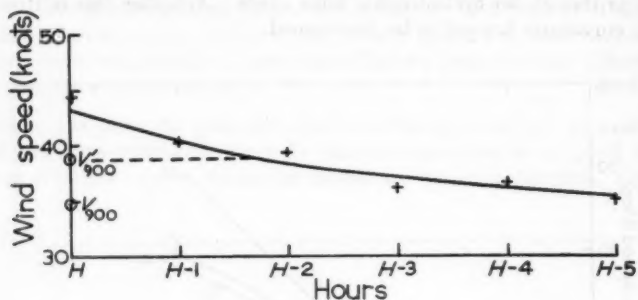


FIGURE 3—GEOSTROPHIC WIND SPEED COMPARED WITH 900 M WIND SPEED IN STEADY ANTICYCLONIC FLOW

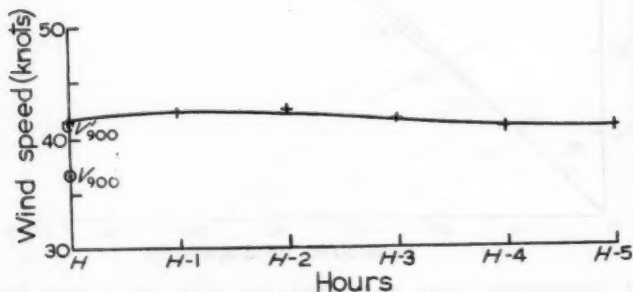
The lag of the wind when the pressure gradient is changing.—In examining the lag of the wind behind a speed which matched the pressure gradient it was thought advisable to exclude cyclonic flow initially since this is complicated by movement of the isobars and by accelerations which are not well represented by the local change of pressure gradient. The investigation was therefore confined to straight and anticyclonic isobars, the assumption being made that since the cyclostrophic term was negligible in steady flow it could equally be disregarded when the pressure gradient was changing. In order to obtain an adequate amount of data, acceleration was defined by a geostrophic wind at least five knots stronger than it was three hours previously, and deceleration by it being at least five knots weaker. In view of the uncertainty of measurement by no means all the occasions appeared in the correct category, but the conclusions should be no less valid on that account.

Figure 4 is based on all occasions in the winters of 1960-61 and 1961-62 when, with straight or anticyclonic isobars, the geostrophic wind at a major

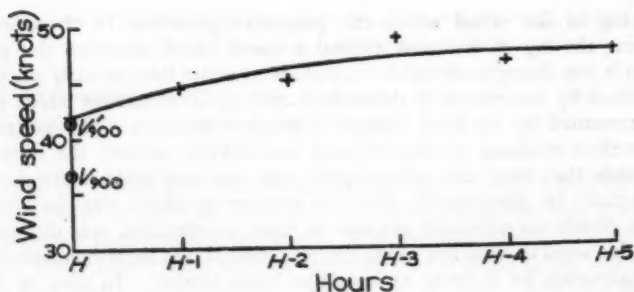
synoptic hour was at least 35 knots. Figure 4(a) shows, for 82 occasions of accelerating flow, the mean geostrophic wind at this hour (H) and at each of the five preceding hours. In drawing a smooth curve to fit the six points account has been taken of the fact that the method of selection introduces an artificially high mean geostrophic wind speed at H and an artificially low one at $H-3$.



(a) Acceleration



(b) Steady flow



(c) Deceleration

FIGURE 4—TIME LAG BETWEEN TRUE WIND SPEED AND GEOSTROPHIC SPEED FOR GEOSTROPHIC WIND SPEEDS OF AT LEAST 35 KNOTS

(The reverse occurs in Figure 4(c)). The reported 900 m wind speed (V_{900}) at H in accelerating air was 34.9 knots, compared with a geostrophic wind at the same time of 44.3 knots. The 900 m wind corrected for systematic error by Figure 1 was 38.9 knots (indicated by V'_{900}) and so was equal to the geostrophic wind nearly two hours before.

Figure 4(c), based on 37 occasions of deceleration, is of interest in that the mean geostrophic wind of 42.0 knots at the synoptic hour was accompanied by $V_{900} = 36.9$ and $V'_{900} = 41.6$ knots. Thus in decelerating air (and with a deceleration about two-thirds the magnitude of the acceleration shown by Figure 4(a)) the adjustment of the wind speed to the weakening pressure gradient was practically instantaneous. Figure 4(b), based on 51 pairs of observations, relates to geostrophic speeds unchanged over the three hours, and here $V_{900} = 36.9$ and $V'_{900} = 41.6$ knots, the latter being practically equal to the geostrophic speed at the time.

Similar results were obtained for geostrophic wind speeds between 20 and 30 knots though the duration of the lag was less certain because of the smaller slope of the curves.

The same wind observations were next analysed according to the magnitude of the 3-hour change in geostrophic speed. Figure 5(a) relates to geostrophic

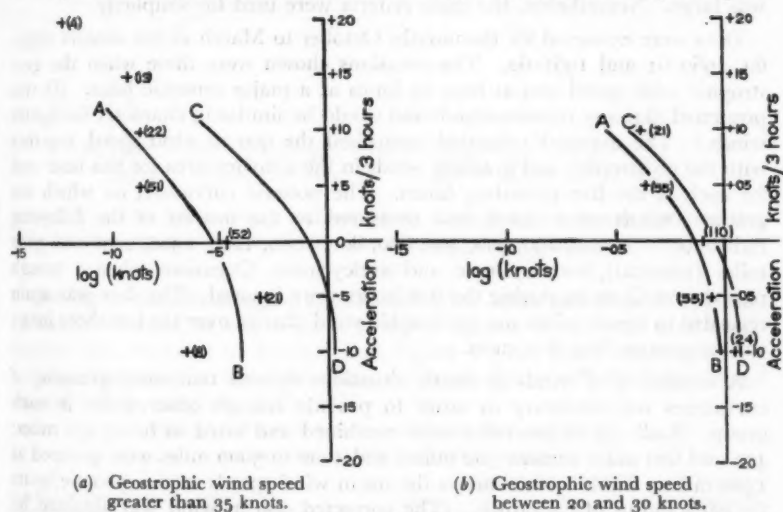


FIGURE 5—LAG OF WIND IN RELATION TO ACCELERATION AS GIVEN BY LOCAL CHANGE OF GRADIENT WIND SPEED

winds of 35 knots or more at the synoptic hour, Figure 5(b) to winds between 20 and 30 knots. The ordinates show changes of speed in knots/3 hours and the abscissae the lag of the 900 m wind below the geostrophic speed. Curves AB relate to V_{900} , the reported 900 m wind speed, and curves CD to V'_{900} , the corrected 900 m wind. It was not possible to obtain more than rough curves AB because of the small number of changes exceeding five knots in three hours, and for this reason curves CD have been drawn simply by applying at all points the correction for the mean 900 m speed, correlation between speed and

acceleration being ignored. The most that should be deduced from the curves CD is the rapid adjustment during deceleration and the fact that during acceleration the wind goes about half way towards meeting the 3-hour geostrophic wind increase. This lag is of course partly inherited at the beginning of the 3-hour period, as is seen from Figure 4(a), which shows that on the average a pressure gradient which increases does so for five hours or more.

The cyclostrophic term in relation to curvature.—So far only straight and anticyclonic flow have been considered, and for two reasons. It seemed likely that with this restriction the changes of pressure gradient experienced by a moving parcel of air would be satisfactorily represented by changes at a fixed point on its trajectory. Furthermore, the conclusion that the cyclostrophic term could be neglected in anticyclonic flow made it possible to assess the lag without taking curvature into account.

The next step was clearly to study the importance of the cyclostrophic term for a range of curvatures, both cyclonic and anticyclonic. Since cyclonic systems are usually more mobile than anticyclonic ones, the criteria adopted hitherto for acceleration or deceleration were unlikely to be so representative of the change in the motion of a parcel of air: trajectories were likely to diverge more from isobars than in anticyclonic flow, particularly when the curvature was large. Nevertheless, the same criteria were used for simplicity.

Data were extracted for the months October to March in the winters 1959-60, 1960-61 and 1961-62. The occasions chosen were those when the geostrophic wind speed was at least 35 knots at a major synoptic hour. (It was presumed that any relationships found would be similar in character for lighter winds.) The material tabulated comprised the 900 m wind speed, together with the geostrophic and gradient winds in the Crawley area for this hour and for each of the five preceding hours. The isobaric curvature, on which the gradient winds were based, was measured to the nearest of the following radii: 100, 150, 200, 250, 300, 400, 600, 800, 1000, 1200, 1500, 2000 and 3000 miles (nautical), both cyclonic and anticyclonic. Occasions when a trough passed over Crawley during the five hours were ignored. The flow was again regarded as steady when the geostrophic wind change over the last three hours was no greater than five knots.

A tabulation of winds in steady situations showed that some grouping of curvatures was necessary in order to provide enough observations in each group. Radii up to 300 miles were combined and listed as being 250 miles; 400 and 600 miles became 500 miles; and 1000 to 3000 miles were grouped as 1500 miles. Table I summarizes the mean wind speeds at the synoptic hours for each radius of curvature. (The corrected 900 m wind was obtained by applying the corrections of Figure 1 to the mean 900 m wind speed, but the gradient winds given are the means of individual readings.)

TABLE I—MEAN WIND SPEEDS IN RELATION TO CURVATURE IN STEADY

	SITUATIONS									
	Cyclonic curvature					Straight Anticyclonic curvature				
Radius of curvature (n. mile)	250	500	800	1500	isobars	1500	800	500	250	
No. of observations	42	63	52	41	61	31	31	11	1	
Reported 900 m wind speed (kt)	34.9	36.0	37.1	37.1	37.9	38.0	32.4	(30.4)	—	
Corrected 900 m wind speed (kt)	36.9	40.3	42.0	42.0	43.1	43.2	35.4	(32.8)	—	
Geostrophic wind speed (kt)	43.4	43.6	42.2	42.8	43.1	42.2	38.5	(37.5)	—	
Gradient wind speed (kt)	32.0	36.6	37.7	39.1	43.1	45.9	45.4	(51.3)	—	

The figures of Table I are plotted in Figure 6. It will be noted that on the anticyclonic side the geostrophic wind appears even to over-estimate the true wind speed. On the cyclonic side the cyclostrophic component was negligible when the radius of curvature was 800 miles or more. For a radius of 500 miles about one-third the cyclostrophic reduction was appropriate, and at 250 miles about one-half, allowing in both cases for some smoothing of the curve.

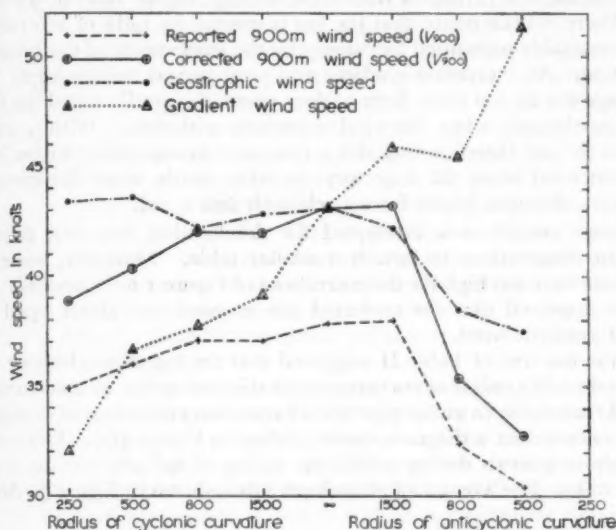


FIGURE 6—MEAN WIND SPEED RELATIONSHIP TO RADIUS OF CURVATURE OF ISOBARS DURING STEADY FLOW WITH GEOSTROPHIC WIND SPEEDS OF AT LEAST 35 KNOTS

The lag of accelerating or decelerating air with straight or cyclonic isobars.—An analysis was made of accelerating flow to ascertain what modification was necessary to Table I and Figure 6 when there was a 3-hourly increase of geostrophic wind of at least 10 knots. The results for cyclonic and straight isobars are given in Table II.

TABLE II—MEAN WIND SPEEDS IN RELATION TO CURVATURE DURING ACCELERATION

Radius of curvature (n. mile)	Cyclonic curvature				Straight isobars
	250	500	800	1500	
No. of observations	16	17	12	28	23
Reported 900 m wind speed (kt)	37.4	39.5	38.1	40.1	37.0
Corrected 900 m wind speed (kt)	42.3	45.6	43.3	46.7	41.8
Geostrophic wind speed (kt)	63.5	52.7	51.7	51.4	48.5
Gradient wind speed (kt)	42.1	42.7	45.2	47.2	48.5
Empirical gradient wind speed (kt)	52.8	49.4	51.7	51.4	48.5
Empirical less corrected 900 m speed (kt)	10.5	3.8	8.4	4.7	6.7

The corrected cyclonic 900 m wind is in good agreement with the gradient wind. This result is almost certainly fortuitous, though it can be accepted as a convenient forecasting rule. The lag in straight flow being 6.7 knots, which is consistent with Figure 4(a) (for which the criteria were slightly different), it is clear that some such lag must occur at all curvatures.

In order to isolate the lag for each radius of curvature, an 'empirical gradient wind' was computed for each column on the basis of the reduced cyclostrophic component found appropriate in steady flow. This empirical gradient wind and its difference from the true wind are given in the last two rows of Table II. As mentioned earlier, geostrophic wind measurements are a little higher than true mean values because of the criterion for acceleration, so four or five knots is perhaps a reasonable average lag for radii of 500 miles or more. There is little doubt that the lag is greater for radii of 250 miles, and this is presumably accounted for largely by the inadequacy of the criterion for acceleration. An increasing gradient and very curved isobars imply that on the average the air has come from a place where the gradient and the flow are weaker, particularly when the wind is backing with time. With pronounced curvature the lag therefore includes a quantity corresponding to the increase in gradient wind along the trajectory: in other words, when the curvature is large the acceleration begins from a relatively low speed.

The same analysis was attempted for decelerating flow but there were insufficient observations to furnish a similar table. Moreover, some of the mean winds were too high for the corrections of Figure 1 to be applied. Nevertheless, it appeared that the corrected 900 m wind was about equal to the empirical gradient wind.

Since the last line of Table II suggested that the lag of accelerating air did not depend on the radius of curvature until this was as low as about 250 miles, it seemed reasonable to group together all remaining occasions of cyclonic flow in order to construct a diagram corresponding to Figure 4(a). This was done for all 5-hour periods during which the radius of isobaric curvature was at least 400 miles. The average of 46 such periods is shown in Figure 7. Although

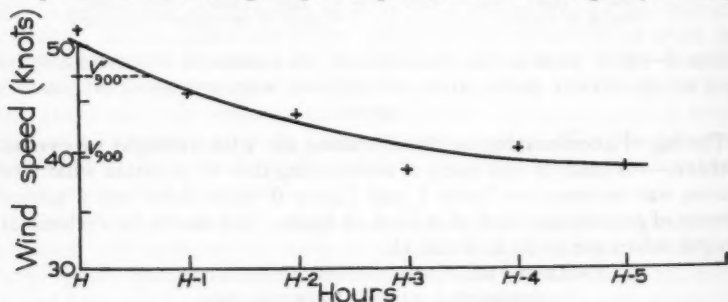


FIGURE 7—TIME LAG BETWEEN TRUE WIND AND 'EMPIRICAL GRADIENT WIND' SPEED

For geostrophic wind speeds accelerating to at least 35 knots and with radius of isobaric curvature (cyclonic) of at least 400 miles.

we know that measured geostrophic winds (and therefore empirical gradient winds) are biased in opposite directions at times H and $(H-3)$, because of the acceleration criterion, the curve leaves little doubt that in this relatively strong and intensifying cyclonic flow the time lag of the wind was less than for straight or anticyclonic isobars. Whether the lag of less than an hour, as compared with 1½–2 hours for straight or anticyclonic flow, should be regarded as a consequence of higher winds, greater acceleration or the shape and movement of the isobars cannot easily be determined.

Summary of results.—

- (i) The 900 m wind speed in British radar reports is an underestimate, the error increasing with speed as shown in Figure 1.
- (ii) With straight or anticyclonic isobars, the pressure gradient being unchanging or weakening, the 900 m wind speed is equal to the geostrophic. The cyclostrophic component is negligible.
- (iii) With straight or anticyclonic isobars and an increasing pressure gradient, the 900 m wind speed is equal to the geostrophic speed of $1\frac{1}{2}$ –2 hours ago.
- (iv) In cyclonic flow, with an unchanging or weakening pressure gradient, the 900 m wind speed is equal to the geostrophic speed when the radius of isobaric curvature is at least 800 miles. With a radius of curvature of roughly 500 miles about one-third the cyclostrophic correction is appropriate, and one-half for a radius of about 250 miles. This result is based on wind speeds of 35 knots or more.
- (v) In accelerating cyclonic flow the 900 m wind speed is as given by (iv) above, but with a time lag of rather less than one hour; except that for radii of isobaric curvature of about 250 miles the wind speed is still lower by a few knots. A fortuitous alternative method of estimating the wind speed is to disregard the time lag and apply the full cyclostrophic correction for isobaric curvature. These results were based on wind speeds of 35 knots or more.

Discussion.—No reasonable explanation was found of the fact that the adjustment between wind speed and pressure gradient depends on whether the gradient is increasing or decreasing. Vertical stability did not seem an important factor since acceleration and deceleration were not significantly related to wind direction. Equally there were not any differences in the average rate of turning of the isobars, which would have introduced different cyclostrophic components.

The apparent unimportance in steady flow of the cyclostrophic term, as illustrated in Figure 6, was first examined as a possible result of vertical transfer of momentum. However, the average vertical shear between 900 m and 850 mb was found to be much the same in both cyclonic and anticyclonic flow, so this factor was discarded.

The most feasible explanation is that the trajectories of the air were significantly different in curvature from the isobars. With no local change in the magnitude of the pressure gradient over three hours it seemed that the departure of the trajectories from the isobars must come from turning of the isobars.

The radius of curvature of a trajectory is related to the radius of a streamline in a formula ascribed by Pettersen² to Blaton:

$$\frac{1}{r_T} - \frac{1}{r_s} = \frac{1}{V} \frac{\partial \beta}{\partial t}$$

where r_T = radius of curvature of the trajectory,
 r_s = radius of curvature of the streamline, here assumed to coincide with the isobar,
 V = wind speed,
 $\frac{\partial \beta}{\partial t}$ = local rate of turning of the wind, here taken to be the direction change in the last three hours.

The average backing or veering of the isobars was calculated for each radius of curvature included in Figure 6. On the cyclonic side the adjustment to the cyclostrophic component was negligible, the largest being an increase of one

knot at 250 miles radius of curvature. There was also practically no correction required for straight isobars. On the anticyclonic side there was a backing of the isobars at all three radii, the average rate being $1.5^{\circ}/\text{hr}$. This was sufficient to give at each radius of curvature a cyclostrophic wind component equal to about half the component found from the isobars. A surprising fact was that the same calculation for accelerating cyclonic flow gave similar results to those for steady cyclonic flow. Thus it appears that the different wind speed relationships between steady and mobile cyclonic situations arise not through differences of isobaric turning but because, as mentioned earlier, the pressure gradient changes significantly along the trajectory. This argument is not conclusive because in the formula given above the curvature of the streamline has been assumed equal to the curvature of the isobar, and this is not strictly true during acceleration.

Reverting to relationships in the steady state, as given by Figure 6, another explanation of the disappearance of most of the cyclostrophic component in cyclonic flow, and of half of it in anticyclonic flow, must be sought. In speculating on the cause it may be recalled that Zobel³ and others have found the wind speed at high levels to be closer to the gradient wind speed than to the geostrophic speed.

A possible solution may lie in the meso-structure of the air flow. It may be that what is regarded on the synoptic scale as smooth, circular flow is in fact somewhat discontinuous, the circle being an approximation to a series of fairly straight paths linked by small troughs or ridges. If this were so the wind speed would be close to geostrophic if the air rounded the troughs or ridges so quickly that only partial adjustment to gradient speed was possible. This could come about in one of two ways, or through a combination of both. An isobar which appears on a chart to be smoothly curved may normally tend towards a polygonal shape, and indeed a close network of reliable pressure readings brings to light many unsuspected irregularities in an isobaric pattern. Alternatively the troughs and ridges in a flow may represent the more pronounced waves in a series of oscillations about an equilibrium line, most of the oscillations resulting in very minor deviations from straight flow and the main turning of the wind being effected by isolated waves.

Supporting evidence for these speculations is hard to find, chiefly because large curvature usually involves the complexities of a fluid situation. It is of interest, however, to note the observations on the variations of wind speed with time, some of which have been summarized by Durst.⁴ The standard vector deviation of wind over one place increases fairly steadily with time after the first hour or so, but within the first hour there is a disproportionately high variation even after allowance has been made for observational errors. This may be evidence of irregular flow such as is suggested in the previous paragraph.

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A SCALE FOR MINIMUM RADIUS OF CURVATURE OF ANTICYCLONIC FLOW

By G. J. JEFFERSON, M.Sc.

The routine preparation of forecast upper air charts suggests that some safeguard is necessary to prevent the drawing of anticyclonic curvature with winds too strong to give a real solution to the gradient wind equation. This article describes the computation of a scale to do this which is in practical use on the forecast bench at London (Heathrow) Airport. The chart used for upper air analysis and forecasting, Form 2219B, is a conformal conical projection with two standard parallels at 30°N and 60°N to a scale of $1:15 \times 10^6$. Broadly speaking the forecast area lies between latitudes 30°N and 70°N for which contours and isotachs are produced at standard levels. One of the most important features of these charts is the placing of jet streams and maximum-wind belts and it is with these strong winds that the critical radius is large and the safeguard most necessary.

The gradient wind equation for anticyclonic curvature is

$$\frac{V^2}{r} - fV + fG = 0 \quad \dots (1)$$

where V = the gradient wind, G = the geostrophic wind, f = the Coriolis parameter $2\omega \sin \phi$, and r = radius of curvature of the air trajectory.

$$\text{Thus } V = \frac{fr}{2} \pm \frac{fr}{2} \sqrt{\left(1 - \frac{4G}{fr}\right)}. \quad \dots (2)$$

There is therefore a minimum value of r which will provide a real solution to the equation. When r is less than this no balance of forces is possible since the cyclostrophic term together with the pressure gradient force becomes too great to allow a balance with the Coriolis term.

The critical condition is therefore:

$$fr = 4G \quad \dots (3)$$

$$\begin{aligned} r &= \frac{2G}{\omega \sin \phi} \\ &= \frac{7.62G}{\sin \phi}, \end{aligned}$$

where r is expressed in nautical miles and G in knots.

Table I columns (a) show the value in nautical miles of the minimum possible values for r for balanced motion with winds from 40 to 200 knots in latitudes 30°N to 70°N. As shown by Freeman¹ these radii must be corrected for map distortion. He has shown that the amount of correction of radius of curvature due to this cause varies not only with the magnitude of the radius and with the latitude, but also with the approximate wind direction, and he evaluates three cases—north-south flow, and east-west flow concave to north and convex to north. Since we are dealing mainly with the upper westerlies, anticyclonic curvature is most commonly convex approximately northwards. Accordingly the values of columns (a) in Table I have been corrected from smooth curves drawn from Freeman's values of r_s in his Table I.¹ These are shown in columns (b) of Table I and are the actual values of the critical radii

of ridges with a north-south axis in nautical miles as measured on the conformal conic projection with standard parallels at 30°N and 60°N.

TABLE I—CRITICAL RADII IN NAUTICAL MILES

Latitude	Wind speed in knots									
	40		50		60		80		100	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
70°N	325	330	405	410	486	490	648	735	810	770
60°N	352	340	440	425	528	506	704	680	866	810
50°N	400	380	500	490	600	578	800	770	1000	965
40°N	480	475	600	590	720	700	960	954	1200	1260
30°N	610	650	762	780	914	1020	1220	1400	1524	1760

Latitude	Wind speed in knots									
	120		140		160		180		200	
	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)	(a)	(b)
70°N	972	890	1134	990	1296	1070	1458	1200	1920	1460
60°N	1056	970	1232	1060	1408	1260	1580	1380	1732	1500
50°N	1200	1160	1400	1350	1600	1500	1800	1700	2000	1900
40°N	1440	1508	1680	1780	1920	2005	2124	2250	2400	2550
30°N	1828	2180	2133	2550	2440	2980	2743	3400	3048	3870

(a) calculated (b) corrected for map distortion.

However, the conformal conic projection is orthomorphic, i.e. the scales of distance along the meridians and parallels are equal at any point. The scale is constant along the parallels but varies with latitude, being correct at 30°N and 60°N, too small between them and too great outside them. The measurement of distances in a north-south direction therefore must involve a small loss of accuracy if the scale at any given latitude is used. Since the radii are, in this case, measured along the meridians the variation of scale is obviously of greatest importance with strong winds and large critical radii. As a first approximation therefore the scale at latitudes of the mid-points of the radii has been taken for the actual measurements on the chart.

The scale of this chart (Form 2219B) in any latitude ϕ is given by the formula

$$\frac{1 + \sqrt{3}}{30 \times 10^8 (\sin \phi + \cos \phi)}$$

which has been used to evaluate the critical radii in inches shown in Table II, which for practical reasons has been taken down to only 40°N.

TABLE II—RADII IN INCHES CORRECTED FOR SCALE TAKING LATITUDE OF MID-POINT OF RADIUS OF CURVATURE

Latitude °N	Wind speed in knots									
	40	50	60	80	100	120	140	160	180	200
70	1.66	2.04	2.46	3.14	3.80	4.33	4.73	5.20	5.85	7.06
60	1.59	2.02	2.40	3.22	3.80	4.53	4.98	5.80	6.56	7.02
50	1.77	2.28	2.69	3.58	4.46	5.46	6.36	7.10	8.07	9.05
40	2.26	2.79	3.32	4.55	6.14	7.40	8.88	10.01	11.60	13.50

Fortunately in the relatively high latitudes, say 60°–70°N where the peaks of most jet-stream ridges occur, it can be readily seen from Table II that the critical radius on the chart shows little change with latitude. Furthermore, on account of the variation of the scale of the chart with latitude, one geostrophic scale will also serve. Figure 1 has therefore been produced as a geostrophic scale which also shows the critical radii which will apply without appreciable loss of accuracy between about 55°N and 75°N, which is the region where it is most commonly required. Measured critical radii are considerably greater

in lower latitudes and Figure 2 shows an additional scale for 50°N which would be suitable for use down to about 45°N and will cover most other ridges for which a scale would be required.

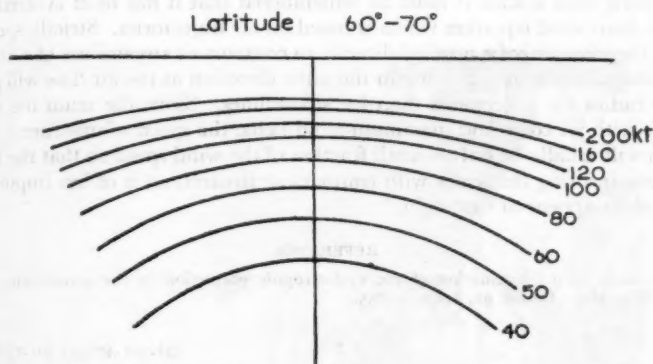


FIGURE 1—GEOSTROPHIC SCALE SHOWING CRITICAL RADII FOR LATITUDE 60°-70°N
For contour interval 120 metres

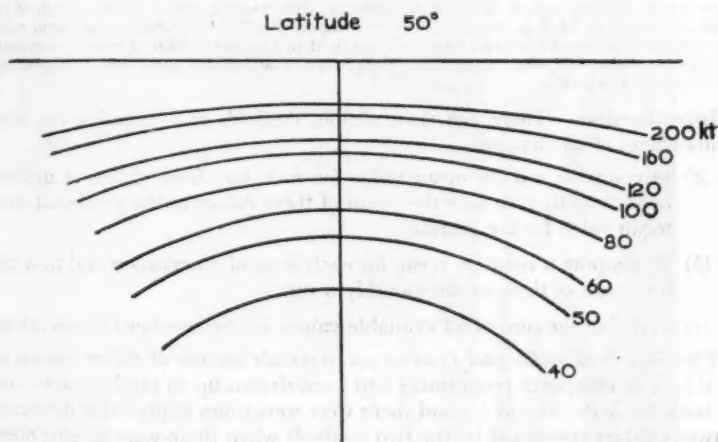


FIGURE 2—GEOSTROPHIC SCALE SHOWING CRITICAL RADII FOR LATITUDE 50°N
For contour interval 120 metres

In drawing isotachs on a forecast upper air chart this scale has an additional use. When r has the critical value for anticyclonic curvature it follows, from substituting equation (3) in equation (2), that

$$V = 2G.$$

Therefore, in using the scale on contours of about the critical radius of anticyclonic curvature, it is known that the gradient wind to be expected round

the crest of the ridge will be twice the value read from the scale. The scale thus ensures, not only that the critical curvature will not be exceeded, but also that adequate allowance is made for the cyclostrophic term when it is not.

In using such a scale it must be remembered that it has been evolved from the gradient wind equation which is based on air trajectories. Strictly speaking it can therefore only be applied directly to contours or streamlines of a stationary system. Any system moving in the same direction as the air flow will give a larger radius for trajectories than for streamlines. Since the main use of the scale is with jet cores and maximum-wind belts, the speed of movement of the system will usually be only a small fraction of the wind speed so that the loss of accuracy in using the scales with contours or streamlines is of less importance than might appear at first sight.

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551.501.45:551.501.75:681.14

THE COMPUTATION OF MONTHLY SUMMARIES OF WINDS FROM INCOMPLETE DATA

By D. DEWAR, B.Sc.

Summary.—A description is given of statistical tests carried out to decide which of two methods, recommended in the *Guide to Climatological Practices*,¹ for computing mean values for combined hours of observations should be used in the production of routine summaries of upper winds by electronic computer. Conclusions reached and some further applications of the results are given.

Introduction.—There are three simple methods of computing combined hours values of an element:

- (a) to compute a daily mean value for each day from values at different hours and then to take the mean of these values as the combined hours mean value for the month;
- (b) to compute a monthly mean for each hour of observation and then take the mean of these as the monthly mean;
- (c) to divide the sum of all available values by the number of observations.

The *Guide to Climatological Practices* recommends the use of either method (a) or (b). The computer programme had been drawn up to produce summaries by both methods (a) and (c) and there were sometimes appreciable differences between values computed by the two methods when there were missing observations at high levels. To provide data upon which to base a decision as to the method to be used for future routine work, modifications were made to the programme so that, after the normal monthly summary had been produced, the data already in the computer could be used to compute vector mean winds by each of the methods (a), (b) and (c), using distributions obtained by omitting a random selection of data from originally complete distributions at the lower levels for which the true values were known.

Random selection procedure.—The procedure adopted was as follows. Only data for the first 10 levels (surface to 250 mb) of an ascent were used. These provided 10 complete distributions for each of which random selections

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Photograph by Mr. R. K. Pilibury

METEOROLOGICAL OFFICE HEADQUARTERS BUILDING

Taken at 1215 GMT on 25 January 1963 after a night when rime was heavily deposited on the trees.



Photograph by Mr. F. A. Gordon

ICE GROWTHS FORMED ON GRASS STALKS

This photograph was taken near the Meteorological Research Flight buildings at Farnborough on 25 January 1963. The thick 'hump-backed' and corrugated formations resulted from water splashing from a burst pipe in the roof above.



Photograph by Mr. F. A. Gordon

An enlargement of part of the photograph (left) showing the peculiar 'caterpillar'-like structure of the ice on the vertical stalks.



Photograph by Mr. E. M. K. Kirk

AN UNUSUAL ICE FORMATION PHOTOGRAPHED AT BRIDGNORTH ON 25 JANUARY 1963

Steam from the heating system is fed back into a condensate tank surrounded by an asbestos housing the bottom of which is seen at the top of the photograph. Much of the steam condensed on the housing forming icicles, but some water dripped on to the handle of a board below forming what was known locally as 'the ice plant'.

of data to be regarded as missing were made by the computer. A random selection of dates for which data were to be considered missing for all hours was made first and was followed by random selections of individual missing values either in one stage or two stages; the first stage selections, obtained by random selection of data from all four hours of observations, had roughly the same number of observations at each hour and were used for what are referred to later in this note as series A tests; the second stage selections taken from two of the hours of observations only, had considerably fewer observations at 0600 and 1800 GMT than at 0001 and 1200 GMT and were used for series B tests. The number of selections made was arranged so that the resulting incomplete data roughly simulated actual high level observations from the point of view of missing data.

Computations.—Using combined hours data for each of the ten levels in turn and omitting 'missing values', the vector mean wind, standard vector deviation, average wind speed and the vector difference between the vector mean winds for complete and incomplete distributions were computed and printed together with the number of observations used. For computing standard vector deviations, components computed by method (a) and mean sums of squares computed in an analogous manner were used.

Conclusions drawn from the results.—Detailed tables of the results have been set out and discussed in a *Climatological Memorandum*.² In this note only a summary of the results and conclusions drawn from them are given.

Tests using data for Lerwick for March 1959.—Ten sets of tests for ten levels were carried out using these data. Two of these were series A tests, the number of observations after the omission of randomly selected data varying from about 22 to 25 at each hour; eight were series B tests with observations varying roughly from 12 to 20 at two of the four hours of observations and from 22 to 25 at the other two hours.

The merits of the three methods were compared using three criteria—totals of mean vector errors at each level; maximum vector errors in any test; number of occasions when vector errors were: (i) less by method (a) than by method (b) and (ii) less by method (c) than by method (b).

Results showed that for distributions of this type the use of method (a) gave better results than method (b) as regards all three criteria, the differences being most marked for the series B tests. Method (c) gave slightly worse estimates of the values than method (b) in the series A tests but appreciably better estimates in the series B tests.

Tests using data for Aldergrove and ocean weather station Juliett.—Three series A tests and six series B tests were carried out using data for Aldergrove and one series A and two series B tests using data for ocean weather station Juliett.

The results confirmed the conclusions based on the tests using values for Lerwick; method (a) again gave, in general, the best estimates of the true values, the departures being most marked for the series B tests. In the series A tests there was little to choose between estimates of the true values obtained by methods (b) and (c) but in the series B tests method (c) gave, on the whole, definitely better estimates.

TABLE I—VALUES AND ERRORS OF ESTIMATES OF V_R AND S.V.D. USING INCOMPLETE 100 MB WIND DISTRIBUTIONS

Year	Month	Lerwick				Stormoway				Crawley			
		Missing obs.		Incomplete values		Missing obs.		Incomplete values		Missing obs.		Incomplete values	
		0001	1200	kt	per ^a cent	0001	1200	kt	per ^a cent	0001	1200	kt	per ^a cent
		GMT				GMT				GMT			
1959	Jan.	1	5	277	11.9	18.7	0.5	—	—	—	—	—	—
	Oct.	2	2	244	16.4	20.6	1.0	0.7	3.1	2	5	304	13.7
	Nov.	2	2	244	16.4	20.6	1.0	0.7	3.1	2	5	304	13.7
	Dec.	1	3	251	26.5	22.8	0.4	0.0	0.0	2	2	267	13.7
1960	Jan.	1	4	301	24.8	27.4	2.5	0.4	1.5	10	10	275	25.3
	Oct.	1	5	281	7.2	11.6	5.7	0.7	6.0	8	6	300	20.5
	Nov.	6	4	272	13.1	18.2	2.8	0.6	3.3	—	—	—	—
	Dec.	10	7	276	19.6	18.9	3.6	1.3	6.9	—	—	—	—
1961	Jan.	6	6	271	23.9	18.7	0.5	1.5	8.0	3	4	295	19.2

^a expressed as percentage of incomplete distributions s.v.d.

ϕ vector error expressed as percentage of incomplete distribution s.v.d.

TABLE II—MISSING WINDS AT 100 MB — SPEED FREQUENCIES

Speed range (kt)	0-9	10-19	20-29	30-39	40-49	50-59	60-69	70-79	80-89
Complete distribution	192	415	365	295	209	106	52	17	6
Missing observations	19	49	56	54	38	14	18	7	3
Percentage lost	10	12	15	18	18	13	35	41	50

Tests using data for Aden for March 1959.—In order to see how results by each method compared when used with a distribution in which there was considerable variation of wind direction with height (a type often experienced in the British Isles in summer), tests were carried out using winds for Aden. In the series A tests where there were roughly the same number of observations at each hour (only two ascents a day were made at Aden) method (a) was rather better than either of the other two methods. In series B tests, with considerably more observations at one hour than at the other, method (a) was definitely worse than method (b) when using data for the surface and 900 mb levels where there was usually a marked diurnal variation of wind; at higher levels method (a) gave, on the whole, better estimates than method (b). Results using method (c) were very similar to those obtained by method (a).

Further discussion of results.—Results of the tests were used to make some deductions as to the possible accuracy of estimates of the standard vector deviation and vector mean wind obtained from incomplete data. Data from a carefully planned series of statistical tests would have been better; a decision as to which method should be used was urgently required however, and the modifications made to the existing programme were of a rather impromptu nature designed only to give comparative results for the three methods.

The maximum errors of estimates of the standard vector deviation (s.v.d.) were expressed as percentages of the true s.v.d. and it was found that, if the s.v.d. of the incomplete distribution is taken as being an approximation to the true value, the error will only occasionally be more than 10 per cent and will often be not more than 5 per cent.

The maximum vector errors of estimations of the vector mean wind (\mathbf{V}_R) were also expressed as percentages of the s.v.d. of the appropriate incomplete distribution, and it was found that maximum errors of from 10 to 20 per cent of the s.v.d. of the incomplete distribution may be expected; for distributions of the Lerwick or Aldergrove type used in the tests maximum errors are likely to be 10 to 15 per cent of the s.v.d. if the numbers of observations at different hours are unequal but only 5 to 10 per cent if the numbers are about the same; for the Aden type of distribution, which shows a considerable variation of wind with height, maximum errors of 15 to 20 per cent are often likely.

Applicability to actual data.—After reading *Climatological Memorandum No. 34* C. L. Hawson suggested that it was doubtful whether results based on a random selection of missing data would apply to actual incomplete data at high levels where, in winter, recorded values are regarded as being strongly biased in favour of light winds as a result of selective factors operating to eliminate strong winds during an ascent.

A limited investigation was carried out using winds at 100 mb to form an idea of the effect of such losses. Days when winds were missing at 100 mb from ascents made at 0001 and 1200 GMT at Lerwick, Stornoway and Crawley in January, October–December 1959 and 1960, and in January 1961 were noted and estimates of the 258 missing winds were made from 100 mb upper air charts. The monthly mean winds and standard vector deviations were computed for the 'completed' distributions, and errors of corresponding values for the incomplete distributions were expressed as percentages of the appropriate incomplete distributions. Results are shown in Table I.

It will be seen that the conclusions regarding likely errors of the s.v.d. computed from an incomplete distribution resulting from purely random losses, namely, 'the error will only occasionally be more than 10 per cent and will often be not more than five per cent', apply remarkably well to these tests also.

Errors of the vector mean wind also are similar to those found in the random tests using data for Lerwick and Aldergrove, only one being greater than 15 per cent, but they do not show the same relation to equality or otherwise of the number of observations at the different hours. This is no doubt because losses of very strong winds which cause large errors may be expected at successive hours of observations and this tends to equalize the number of observations.

It seemed likely that the general agreement between results for purely random losses and actual losses at 100 mb could be ascribed to the fact that strong winds in the troposphere are usually associated with light winds in the stratosphere, and that this leads to the actual losses approximating to random losses. To examine this supposition, frequencies of wind speeds (in 10-knot ranges) were extracted for the complete distribution and for the missing winds. The results are shown in Table II. Up to speeds of about 60 kt the percentage losses, though increasing with speed, did not depart very much from purely random values (about 14 per cent for each range). At higher speeds the losses were highly selective, but the number of occasions when there were observations in these ranges was small (75 out of 1657 observations) and this resulted in total losses being similar to random losses.

These investigations showed that at 100 mb although there was a selective loss of winds, the results of the random tests could have been used to get an idea of the likely errors of the vector mean winds and standard vector deviation computed from the remaining observations. How far this would apply to data for still higher levels is uncertain as presumably selective losses increase with height producing distributions which become less and less random; a tentative suggestion is that, as long as the number of missing observations (and other parameters) are similar to those of the random tests, errors of estimates made from the remaining data may be expected to be similar to those found in the random data tests.

Conclusions.—For routine summaries of upper winds produced by an electronic computer, where the arithmetic involved is a minor consideration and unique instructions are required, the use of method (a) for the computation of combined hours summaries of wind is recommended. If arithmetic is a consideration the use of method (b) can be regarded as satisfactory when there are roughly the same number of observations at each hour. For summaries of an element for which the diurnal variation is greater than the interdiurnal variation, method (b) should be used.

Rough estimates of the maximum vector error of a vector mean wind computed from an incomplete distribution can, subject to certain restrictions, be made from the standard vector deviation of the incomplete distribution.

Acknowledgement.—The author is indebted to Mr. P. B. Sarson for help with the random selection procedure and to Mr. F. E. Lumb for some very helpful criticism and suggestions during the preparation of this note.

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551.524.37:551.584.2:551.588.2

THE HOUGHALL FROST HOLLOW

By A. J. W. CATCHPOLE, B.Sc.
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Introduction.—Frost hollows are common features of the British landscape but the opportunities for studying their climatic conditions are limited. Valley bottoms and basins are often poor sites for meteorological stations since they produce the extremes which must be avoided by the normal observer. Some fairly long-term records from frost hollows do exist however and these can be used to describe the seasonal variations in these extremes. In this way a valuable reference is provided for the large amount of short-term experimental work which is being done in frost hollows. The account of the Rickmansworth frost hollow by Hawke¹ is particularly outstanding. Using a 13-year record of temperature from the Chess Valley Hawke was able to demonstrate the relative continentality of the thermal conditions at Rickmansworth. In this paper a comparison will be made between the temperature records in the Houghall frost hollow and those of a neighbouring summit station at Durham. Later, brief comparisons between the conditions at Houghall and Rickmansworth will be drawn.

The stations.—The locations of the climatological stations at Houghall Agricultural College and Durham Observatory are shown in Figure 1. Houghall lies roughly 200 feet below Durham and less than a mile distant to the south-east. The site of Durham Observatory and its meteorological record have been described in detail by Manley.² Briefly, it occupies an open summit on a plateau surface into which the Wear is entrenched by some 200 feet. Houghall is located on this valley floor at a point where it is flanked by steep escarpments at the edge of the plateau. The only extensive woodland in the area is on these escarpments. The remainder of the area is fairly open farm land. In the vicinity of Durham the valley narrows to a gorge.

The situation of Houghall is typical of much of the valley farm land in the north-east of England. On these river side 'haughs' (from the Anglo-Saxon 'healh', meaning 'flat land beside a river') occurs some of the best meadow and arable land in the district. This is particularly true of the Wear and Tyne valleys which are deeply entrenched over most of their courses. It is hoped that this study of the thermal properties of a typical example will illustrate the nature of the general conditions prevailing over these valuable areas.

Manley³ has mentioned some of the unusual properties of the monthly mean and extreme temperatures at Houghall and he first drew attention to the relative continentality of its climate.

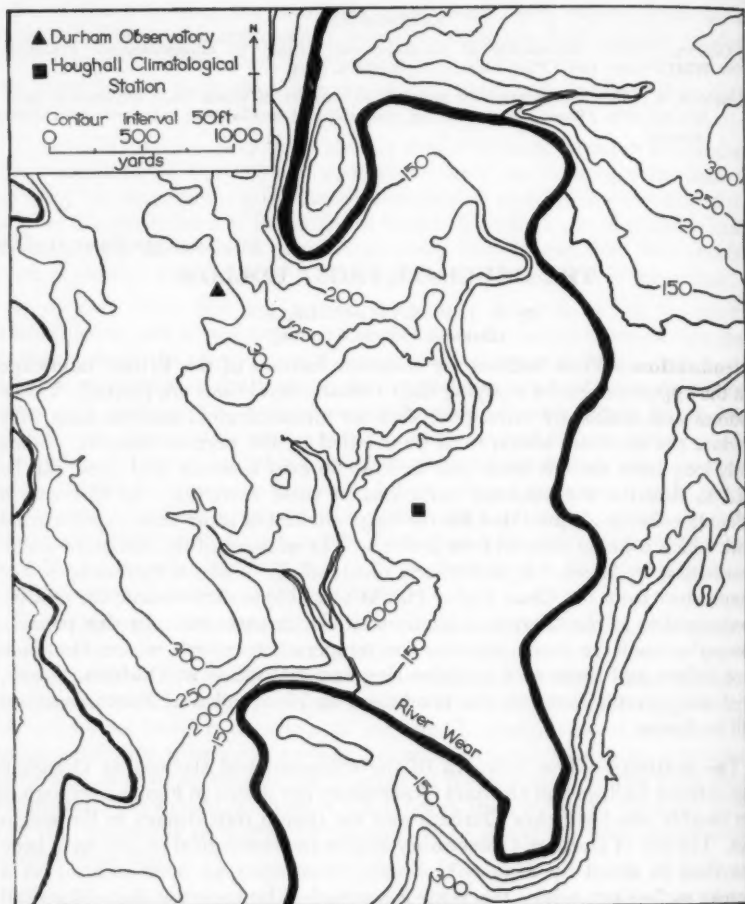


FIGURE 1—RELIEF MAP SHOWING LOCATION OF HOUGHALL CLIMATOLOGICAL STATION AND DURHAM OBSERVATORY

The records.—The meteorological record at Durham Observatory is one of the oldest in the country, dating continuously from 1850. Observations were first made at Houghall in 1925. A twenty-year period, March 1925 to February 1945, is used in this comparison. This period was relatively mild over the country as a whole since it excludes the very cold decade 1885 to 1895. Consequently it is difficult to compare the absolute minima at Durham and Houghall during this period with the values from other stations since these are usually taken from different periods. Where necessary some comparisons are drawn from longer periods.

The daily screen and grass minimum temperatures have been used in this comparison.

Comparison of the daily screen minimum temperatures.—The monthly extreme screen minimum temperatures were lower at Houghall and the difference was greatest in winter (Table I).

TABLE I—EXTREME MONTHLY SCREEN MINIMUM TEMPERATURES (°F) 1925-45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Houghall	-6	-1	8	18	21	28	32	32	26	19	16	10
Durham	3	11	15	22	24	30	34	35	30	22	20	18
Difference	9	12	7	4	3	2	2	3	4	3	4	8

Houghall is clearly subjected to particularly low extremes and this will be emphasized by a few random comparisons with other stations. Bilham⁴ lists Houghall as being one of the twelve stations in the British Isles with a below-zero minimum screen temperature between 1895 and 1938. Eight of the remaining twelve stations were in Scotland. In March 1947 Houghall recorded a minimum screen temperature of -6°F which was 3°F colder than the previous March record for the British Isles. In 1959, a year taken at random, Houghall recorded more ground frosts than any other station reported in the *Annual Summary of the Daily Weather Report*. Only one other station came within 80 per cent of the Houghall total.

We now have an indication of the severity of the extreme conditions at Houghall; it remains to estimate the importance of these in the mean monthly and annual values.

The contrast between the mean monthly screen minimum temperatures at the two stations was smaller than that between the extreme monthly screen minima (Table II).

TABLE II—MEAN MONTHLY SCREEN MINIMUM TEMPERATURES (°F) 1925-45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	30.8	32.0	33.7	37.0	40.4	46.4	50.5	50.0	45.8	40.4	35.5	32.5	39.5
Durham	32.0	32.7	34.2	37.2	41.0	46.5	50.9	50.5	46.5	41.2	36.7	33.8	40.3
Difference	1.2	0.7	0.5	0.2	0.6	0.1	0.4	0.5	0.7	0.8	1.2	1.3	0.8

These differences are surprisingly small. Standard-error testing proved significance of the difference only in January, September, October, November December and the mean annual values. The relatively small differences in February and March may be due to a higher frequency of wind frosts affecting both stations equally in those months. Later we shall find that the contrast between the grass minimum temperatures is also greatest in October, November and December. This may be partly caused by a more persistent snow cover providing insulation for the grass thermometer in the valley bottom in January and February. This would seem to happen on some cold nights when Durham has recorded grass minimum temperatures several degrees lower than those of Houghall during calm conditions.

The difference between the two sets of observations in Table II also seems to be reduced by the occasional occurrence of particularly warm nights at Houghall. Being higher and more exposed Durham will record lower minima than Houghall during periods of cold winds. Of course this contrast will be reduced by turbulent mixing. This greater range of minimum temperatures in the frost hollow can be seen in Figure 2 which shows the monthly frequency distributions of daily minimum temperatures at Houghall (Figure 2(a)), Durham (Figure 2(b)) and the percentage difference between these in Figure 2(c). In all months Houghall has a higher percentage of very high and very low minima but the contrast is greatest in winter and in the case of the low minima.

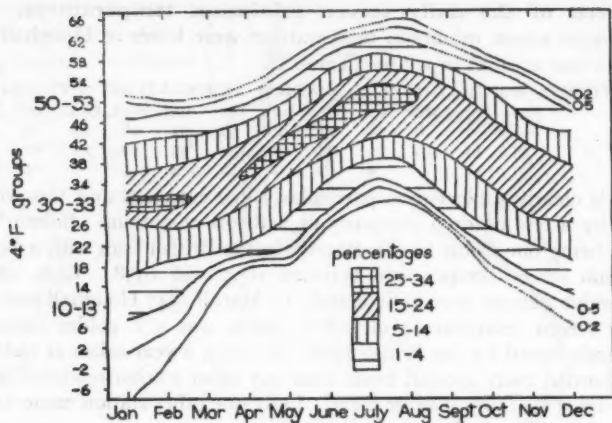


FIGURE 2(a)—MONTHLY FREQUENCY DISTRIBUTION OF SCREEN MINIMUM TEMPERATURES 1925-45 AT HOUGHALL

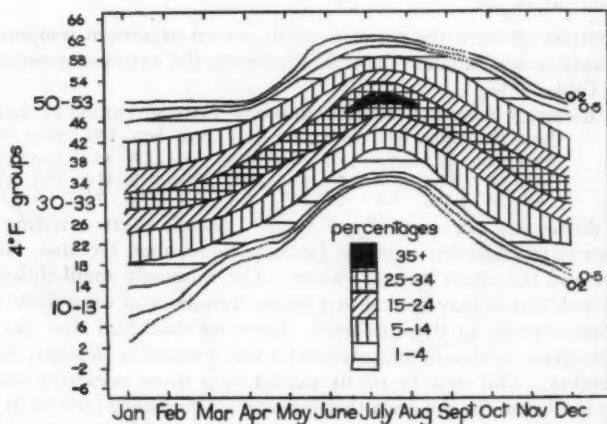


FIGURE 2(b)—MONTHLY FREQUENCY DISTRIBUTION OF SCREEN MINIMUM TEMPERATURES 1925-45 AT DURHAM

A numerical estimate of the greater variation in minimum temperatures in the frost hollow is contained in the curves of monthly standard deviation of daily minimum temperatures (Table III).

TABLE III—MONTHLY STANDARD DEVIATION OF DAILY SCREEN MINIMUM TEMPERATURES ($^{\circ}$ F) 1925-45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	8.2	7.5	6.3	6.1	6.5	5.9	5.4	5.7	7.0	7.2	6.9	6.8	9.6
Durham	6.6	6.2	5.5	5.2	5.4	4.9	4.3	4.5	5.8	6.1	5.5	5.8	7.7

Now the greatest contrast is in January but November, October and September are again more severe than February, March and April respectively.

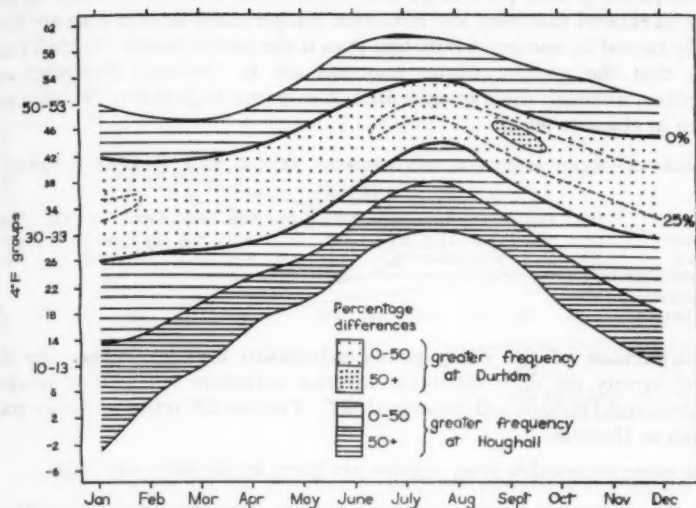


FIGURE 2(c)—PERCENTAGE DIFFERENCES BETWEEN FIGURES 2(a) AND 2(b)

The contrast between the frequencies of air frosts at Houghall and Durham also indicates relative severity in the valley bottom. The definition of an air frost is based on a screen minimum temperature of 32°F and below. Champion⁵ has discussed the merits of the various definitions of ground frost in detail and favours an upper limit of 32°F . Hawke¹ and Hogg⁶ also concern themselves with 'days with a minimum temperature of 32°F and below'.

TABLE IV—MEAN MONTHLY FREQUENCIES OF AIR FROSTS. 1925-45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	17.5	14.4	12.7	6.7	4.1	0.6	<0.1	<0.1	1.2	4.7	10.5	15.2	87.7
Durham	15.9	13.3	11.5	5.7	2.6	<0.1	0.0	0.0	0.3	2.9	6.9	12.2	71.6

Houghall persistently suffers more air frosts than Durham especially in November and December. The total difference is not large, particularly when compared to other local contrasts based on altitude or distance from the sea. This will be illustrated with some examples given by Lewis.⁷

TABLE V—SEASONAL FREQUENCIES OF AIR FROSTS (DAILY SCREEN MINIMUM TEMPERATURE 32°F OR BELOW)

	Spring (Mar. Apr. May)	Summer	Autumn	Winter
Houghall	23.5	0.7	16.4	47.1
Durham	20.0	<0.1	10.1	41.6
Tynemouth*	6.1	0.0	2.9	14.9
Dun Fell* (north Pennines)	60	1	29	78
Cockle Park* (Northumberland)	20.4	<0	9.7	39.7

* after Lewis.

The mean annual number of days with air frost at Houghall is only 64 per cent of the Rickmansworth value. The relatively small contrast between Houghall and Durham in Table V may be partly due to the fact that it ignores the severity of the frosts. In fact a greater difference between the two emerges when we consider the mean monthly day-degrees of frost.

Perhaps the greater percentage differences in the summer half year are due to the likelihood that very low minimum temperatures at that time are more usually caused by nocturnal radiation than is the case in winter. Table VI also shows that the greatest winter contrasts are in October, November and December, although these months are not as severe as January, February and March in absolute terms.

TABLE VI—MEAN MONTHLY DAY-DEGREES BELOW 32°F (SCREEN MINIMUM) 1925-45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	111.0	78.8	55.0	24.5	13.4	0.5	0.0	0.0	2.5	15.5	40.5	74.5	421
Durham	78.5	57.5	38.2	12.7	5.1	0.1	0.0	0.0	0.3	6.6	22.5	45.1	267
Durham as a percentage of Houghall	71	73	70	52	38	20	—	—	10	43	53	61	63

Comparison of the daily grass minimum temperatures.—For the sake of brevity the daily difference in grass minimum temperature between Houghall and Durham will be termed dT . Positive dT refers to higher grass minima at Durham.

The extreme monthly grass minima are given in the following table.

TABLE VII—EXTREME MONTHLY GRASS MINIMUM TEMPERATURES (°F) 1925-45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Houghall	-11	-7	4	11	12	20	26	26	20	15	9	5
Durham	-2	2	7	14	16	23	26	28	24	15	12	12

Except in January, February and December these differences are rather small. October is particularly surprising in this respect in view of the considerable contrasts experienced in that month in the case of the air minima. Ground frosts have occurred at both stations in all months. Later we shall find however that, with the exception of January and February the extreme minima at Houghall are considerably higher than those at Rickmansworth.

TABLE VIII—MEAN MONTHLY VALUES OF dT (°F) 1925-45

Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
3.2	2.7	2.5	2.0	1.3	0.5	0.8	1.5	2.0	3.3	3.5	3.5	2.2

All of these differences are 'positive'. The mean monthly grass minima are consistently lower in the frost hollow. November and December are again particularly severe months in the frost hollow. Since grass minimum temperatures represent extremes it is not surprising to find that the differences indicated in Table VIII are greater than those in Table II.

There is a tendency for a greater range of dT in winter than in summer. In Figure 3 the frequency distributions of dT for the winter and summer half years have been plotted as continuous curves. The simplification of the temperature scale was intended to smooth the minor irregularities. There is a lag of approximately 2 °F between the two curves. This lag may give an indication of the greater severity of winter conditions in the frost hollow compared with those of summer. Only 13 per cent of the winter values of dT occurred at the mode in Figure 3 compared with 16.5 per cent in summer. This is not a large difference but it indicates a greater range of values in winter which agrees with the results on air minima shown in Figure 2.

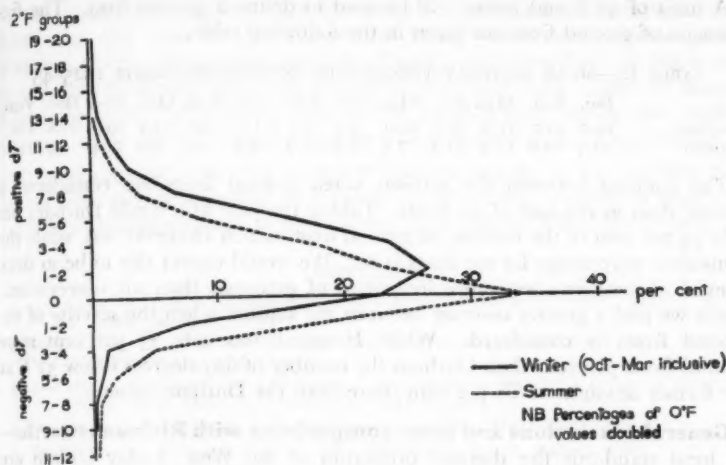


FIGURE 3—PERCENTAGE FREQUENCY DISTRIBUTIONS OF dT 1925-45

In Figure 4 the percentage frequency distributions of dT for selected periods are compared with the percentage mean annual frequencies. Winter is outstanding mainly for its high percentage of large positive values of dT . In winter there are a large number of occasions when the grass minima at Houghall are considerably lower than those at Durham. The opposite applies in summer and there is a high frequency of relatively high grass minima at Houghall. In Figure 4C this contrast between winter and summer is seen to be magnified when January and July, the two extreme months, are compared. The transitional features of April and September are shown in Figure 4A.

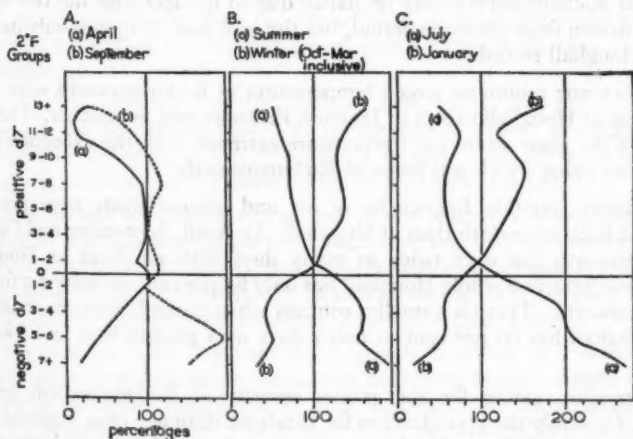


FIGURE 4—PERCENTAGE RATIO BETWEEN FREQUENCY DISTRIBUTION OF dT FOR SELECTED PERIODS AND MEAN ANNUAL VALUES, 1925-45

A limit of 32°F and below will be used to define a ground frost. The frequencies of ground frost are given in the following table.

TABLE IX—MEAN MONTHLY FREQUENCIES OF GROUND FROSTS 1925-45

	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Houghall	24.5	22.7	21.6	15.7	10.0	3.7	0.7	1.0	6.0	13.2	19.2	22.6	162
Durham	18.5	18.0	17.5	12.2	7.5	2.9	0.7	0.9	3.4	8.2	13.4	16.9	119

The contrast between the stations when ground frosts are considered is greater than in the case of air frosts. Taking the year as a whole Durham has only 74 per cent of the number of ground frosts which Houghall has, while the equivalent percentage for air frosts is 82. We would expect this to be so since ground observations are more indicative of extremes than air observations. Again we find a greater contrast between the stations when the severity of the ground frosts is considered. While Houghall has only 33 per cent more ground frosts per year than Durham the number of day-degrees below 32°F at the former amounts to 66 per cent more than the Durham value.

General conclusions and some comparisons with Rickmansworth.—

By local standards the thermal properties of the Wear Valley bottom are continental. Mean minimum temperatures are relatively low and are subject to greater variation in the frost hollow as compared to conditions on the neighbouring plateau surface. These contrasts apply particularly in early winter. October, November and December are months of greater relative coldness in the frost hollow although in absolute terms the most severe conditions prevail in January, February and March.

In comparison with conditions at Rickmansworth Houghall cannot rank as a severe frost hollow. The monthly mean screen minimum temperatures at Houghall are considerably higher than those at Rickmansworth. The difference between the two amounts to a maximum of 5.1°F in September and a minimum of 2.2°F in May and June. The mean annual difference is 3.1°F. These lower means at Rickmansworth may be partly due to the fact that the two records are not drawn from the same period, but the cold year of 1929 is only included in the Houghall record.

The extreme minimum screen temperatures at Rickmansworth were lower than those at Houghall except in January, February and September. The same is true of the grass minimum temperature extremes with the exception of the September value which was lower at Rickmansworth.

The mean monthly frequencies of air and ground frosts were generally higher at Rickmansworth than at Houghall. In April, September and October Rickmansworth has over twice as many days with air frosts as Houghall. Taking the year as a whole Houghall has only 64 per cent as many air frosts as Rickmansworth. There is a smaller contrast when ground frosts are considered and Houghall has 80 per cent as many days with ground frost as Rickmansworth.

The precise reasons for the greater severity at Rickmansworth are not known. Certainly the opportunities for katabatic drainage on a 'regional' scale are better in the Chiltern dip-slope valleys than in a widely meandering valley like that of the Wear (Heywood)⁸. The most striking differences exist between Houghall and Rickmansworth when means are considered. Perhaps this is due

to the occasional relatively high minimum temperatures at Houghall. It is likely that the more deeply entrenched Wear Valley will provide greater shelter than the Chess during periods of cold, windy weather. If this is so it would tend to elevate the mean minima at Houghall with respect to those at Rickmansworth. The gravel soils of the Chess Valley would also tend to produce lower minima than the heavier silts and clays of the Wear Valley.

It would appear from this evidence that the farmer in the northern frost hollow will only occasionally be subjected to the severe conditions which are rather more commonplace to his southern counterpart at Rickmansworth.

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REVIEWS

Meteorologie der Strahlströme (Jet Streams), by E. R. Reiter. 10 in. x 7 in. pp. xi + 473, illus., Springer-Verlag, Wien 1, Mölkerbastei 5, 1961, Price: £12.

A great deal has been written about the jet stream since evidence of this feature of atmospheric flow was first uncovered and studied in detail shortly after the end of World War II. Nevertheless, it is at first sight somewhat surprising to find an entire textbook of over 400 pages devoted to this one phenomenon.

Yet at close quarters it is soon realized that this work is no ordinary discourse on the jet stream alone. It constitutes, in effect, a comprehensive treatment of the dynamics of atmospheric motion, with the jet stream providing the motif behind the presentation of the work as a whole.

The jet stream is indeed a crucial fact of our planetary atmosphere. It can be used as a practical example to be related in one way or another to many facets of theoretical dynamic meteorology, in addition to synoptic meteorology and general circulation climatology. A treatise on the jet is therefore by nature a study of these three basic disciplines of meteorological science.

If anything the book is almost too thorough touching as it does upon the various methods of measuring winds, and discussing at some length the errors and variations which may occur in wind measurement. Long passages of the text are printed in smaller type so that they can be identified by the reader and omitted on first reading if desired. The material is up to date including the results derived from the famous "Project Jet Stream" aircraft runs across jet stream cores, about which Dr. Reiter has written in the research journals.

The book is costly but extremely well produced and profusely illustrated with excellent and informative diagrams. It is a classic of its kind and should be read by students and research workers in meteorology and others concerned with atmospheric motion or fluid dynamics. There are some sixty pages of references which constitute a very useful bibliography of the literature on the subject.

A. H. GORDON

PUBLICATION RECEIVED

Meteorological Memoirs. Vol. I, Meteorological Department, Republic of Iraq. 11 in. x 8½ in., pp. (ii) + 165, *illus.*, Directorate General of Civil Aviation, Meteorological Department, Ministry of Communications, Republic of Iraq, 1962.

This is the first volume of a new series. It comprises 15 scientific papers by Iraqi meteorologists, covering many aspects of the meteorology of Iraq.

Aeronautical descriptive climatological memoranda, Federal Meteorological Department, Rhodesia and Nyasaland. 12½ in. x 7¾ in., pp. 15, *illus.*, Ministry of Transport, Salisbury, Rhodesia, 1961.

OFFICIAL PUBLICATIONS

The following publications have recently been issued:

SCIENTIFIC PAPERS

No. 16—*An experiment in operational numerical weather prediction*, by E. Knighting, B.Sc., G. A. Corby, B.Sc. and P. R. Rowntree, B.A.

The paper describes an operational experiment in numerical weather forecasting carried out within the Meteorological Office from November 1960 to June 1961 using the electronic computer METEOR. Initial data for 0001 GMT were analysed objectively within the computer for three levels in the atmosphere and forecasts based on these data were computed for 0600 GMT on the following days. A novel feature of the experiment was that the forecast computation was interrupted to allow the inclusion of such 0600 GMT data as were available at the appropriate stage in the calculation. Statistical measures of the accuracy of the forecasts are given together with several examples of the computed forecasts.

No. 17—*Extremes of wind shear*, by A. F. Crossley, M.A.

Values of large horizontal and vertical shear are gathered from a survey of appropriate publications and are discussed with reference to the distance over which each is sustained. In the vertical, curves of extreme shear are estimated for north-west Europe and for the U.S.A. Use is made of recordings of the Crawley automatic radar theodolite over a period of 12 months; these are analysed to obtain frequency levels of shear over various height intervals up to 10,000 feet, and a method is described for estimating corresponding long-term frequencies for other places, in particular for New York. In the horizontal, the data have been applied to obtain a curve of extreme shears in relation to distance over which they are measured. There is some discussion of anticyclonic shear with reference to stability criteria; although several instances are noted of anticyclonic shear apparently greater than the Coriolis parameter, in no case is the excess beyond the range of possible observational errors.

GEOPHYSICAL MEMOIR

No. 106—*A meso-synoptic analysis of the thunderstorms on 28 August 1958*, by D. E. Pedgley, B.Sc.

This Memoir describes the structure and evolution of some particularly well defined medium-scale anticyclones and depressions (with diameters of 50 to 100 miles) which accompanied the widespread thunderstorms over England on 28 August 1958. These meso-scale features closely resembled those observed in other countries, notably the U.S.A. and Japan. Sufficient data were available to construct a "model" thunderstorm meso-system, and the physical processes involved in its life-cycle are discussed. The specialized techniques of analysis used show that considerably more detail can be deduced from data available as routine than is currently obtained by day-to-day synoptic weather analysis.

LETTER TO THE EDITOR

Analysis of forecasting in the Mediterranean

Mr. Kirk, in his very clear and interesting article "Analysis of a weak discontinuity at Malta, 2 September 1960" published in the *Meteorological Magazine* of February 1963, emphasizes the serious limitations of the surface synoptic chart as an aid to analysis in the Mediterranean. As long ago as 1950, I wrote an article "Upper frontal analysis in the Mediterranean", (*Meteorological Magazine* 1950) in which I drew attention to the value of upper air charts, in particular the 850 millibar chart, for the purpose of analysis and forecasting. However, to judge from my experience as a Senior Forecaster at London (Heathrow) Airport during the years 1955-59, I very much doubt whether, with the exception of those forecasters who have actually worked at Luqa, the importance of the 850 mb chart and other upper air charts as analysis and forecasting tools in the Mediterranean, is even yet fully appreciated. As Mr. Kirk points out, few examples are available to illustrate the nature of the difficulties of analysis in the Mediterranean area. I therefore warmly welcome this article, strongly recommend it for careful study by all meteorologists who are liable to be concerned with forecasting in the Mediterranean, and hope it will be followed from time to time by further instructive examples.

Meteorological Office, Bracknell.

F. E. LUMB

OBITUARY

Mr. Percy Powell.—It is with deep regret that we have to report that Mr. Percy Powell, "Pip" to all his friends and associates, died on 1 February 1963. When driving home after morning duty he was in collision with a coach, and sustained fatal, though mercifully instantaneous, injuries.

Mr. Powell who was 61 when he died, entered the Meteorological Office in 1919 as a Boy Clerk and spent the next seven years in the Forecast Division, being promoted Technical Assistant in 1922 and then regraded as a Grade III Clerk in 1923. In the years before the war he served at several stations (Cardington, Lympne, M.O.2 again, Andover and Wyton) being assimilated as Assistant Grade III in 1935 then promoted to Grade II in 1938.

He was mobilised at the outbreak of war and served for a time with No. 2 Group in France returning to this country to serve both as a civilian and as a Flight Lieutenant in the R.A.F.V.R. at a number of formations. After his release from the R.A.F.V.R. in 1945, and assimilation as Experimental Officer in 1946, he served first at H.Q. No. 3 Group and was then posted to Germany where he was promoted to Senior Experimental Officer in 1949. Returning to England in 1952 he spent the rest of his life at H.Q. No. 3 Group Mildenhall, retiring in 1962 but being re-employed as a Disestablished Experimental Officer.

During his last few years Mr. Powell did much work as the Regional Representative of the I.P.C.S.

"Pip" was a most kindly, friendly and helpful man. His colleagues at Mildenhall had much respect and affection for him, and the R.A.F. were always very happy to receive his sound level-headed advice. He will be mourned by his many friends throughout the Office and elsewhere.

Deep sympathy is extended to his widow and family in their great sorrow.

D. W. J.

CORRIGENDA

Under the heading at the top of p. 310 of the November 1962 *Meteorological Magazine*, 1957 to 1961 should read 1959 to 1961.

On the front cover of the February 1963 *Meteorological Magazine*, No. 1086 should read No. 1087.

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